Local, non-linear Interaction Region Correction Studies

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1 INTRODUCTION

The main goal of the interaction Region (IR) Correction system is to improve the performance of a collider by:
(i) correcting locally the effect of the **nonlinear field errors** in the Interaction Region (IR) triplets, and beam separation dipoles (DX and D0 in RHIC).
(ii) correcting locally **coupling effects** arising from field errors and misalignment in the IR magnets.
IR Correction significantly improves the dynamic aperture in simulation (RHIC and LHC). However, given the inherent complexity of nonlinear effects and the lack of straightforward observables, possible improvement of machine performance requires careful planning and machine studies to achieve the goal.

I will overview here the method (*action-kick minimization*) used for IR corrections, the implementation of the correction system for RHIC and its comparison with the system proposed for the LHC. I will then describe the modeling studies that guided the design of the system as well as modeling studies planned for the commissioning. A plan for IR machine studies is then discussed. The plan is conceptually divided in a *"commissioning phase"*, that is, the steps necessary to make the system operational, and a *"study phase"* proper, in which parameter spaces as well as their effect on the quality of correction are explored. Finally, I discuss how IR machine studies may form the basis for collaborative studies.

2 THE CORRECTION METHOD

The field quality of magnets in the IR's and beam-beam effects are fundamental factors limiting the performance of hadron colliders. The IR Correction system addresses the first factor and corrects the effect locally, taking advantage of the fact that the error sources are local and that there are well defined phase relations between the IR triplets. The action-kick method (first proposed by J.Wei [1]) minimizes the action-angle kick produced by the IR magnets at every order. The action-kick is defined as:

$$\Delta J_x = -\sum_{k,m=-\infty}^{\infty} ik\Delta J_{km}$$

$$\Delta J_y = -\sum_{k,m=-\infty}^{\infty} im\Delta J_{km}$$

$$\Delta J_{lm} \approx -\int ds A_{km} e^{ik\int_0^s \frac{1}{\beta_x}ds'} e^{im\int_0^s \frac{1}{\beta_y}ds'}$$

The above expression for the actions greatly simplify by observing that actions are almost constants of motion and that there are simple phase relations within the IR magnets: there is almost no phase advance in within one triplet and a phase advance of about π between triplets in one IR. It can be demonstrated that, with these approximations, a minimum of *2 correctors per multipole* is needed in every IR to correct for the contribution of all IR magnets. By placing the correctors in symmetric locations around the Interaction Point (IP), and exploiting the IR optics anti-symmetry, the one next to a maximum of β_x will be effective horizontally and the one next to a maximum of β_y vertically. The *strengths of correctors* are obtained by minimizing the following quantities:

$$\int_L C_z c_n ds + (-1)^n \int_R C_z c_n ds \qquad z = x, y$$

$$C_x = \begin{cases} \beta_x^{\frac{n}{2}} & \text{for } b_n \\ \beta_x^{\frac{n-1}{2}} \beta_y^{\frac{n}{2}} & \text{for } a_n \end{cases}$$

$$C_y = \begin{cases} \beta_y^{\frac{n}{2}} & \text{for even } b_n \text{ or odd } a_n \\ \beta_x^{\frac{1}{2}} \beta_y^{\frac{n-1}{2}} & \text{for odd } b_n \text{ or even } a_n \end{cases}$$

It is worth noticing that the action-kick minimization method does not account for *feed-down* effects. The effect of feed-down has to be evaluated by simulation, at design time, and machine studies, at operations time.

3 THE RHIC IR CORRECTION SYSTEM

The RHIC IR correction system consists of nonlinear correction layers located in the C1, C2 and C3 corrector packages located next to the IR triplets, and related power supplies.
All IR's in the Blue and Yellow rings are equipped with correction layers, but in run 2000 only layers at 6 and 8 o'clock (where the large experiments are located) are connected to 50A corrector supplies. A detailed layout of the IR regions can be seen in Figure 1.
In addition, 2 skew quadrupoles per IR (both in the Blue and Yellow Ring) are installed in every C2 package. All IR skew quadrupoles have a 50A independent supply, for a total of 24. These skew quadrupoles to compensate the local coupling

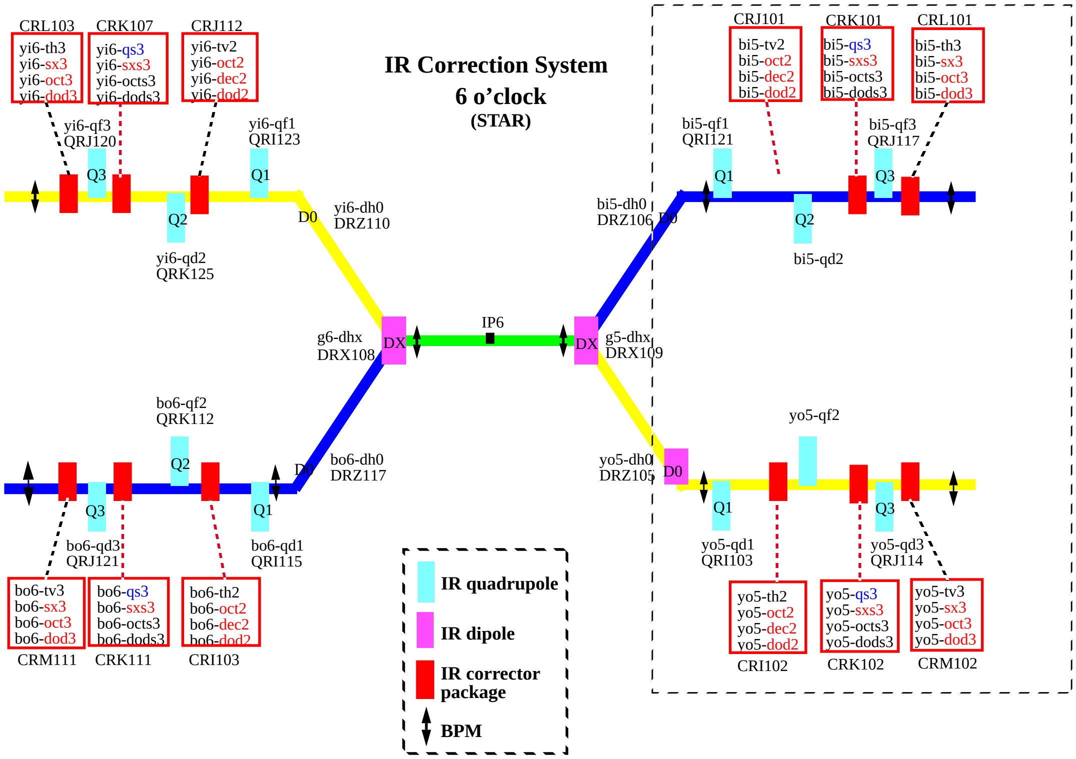

Figure 1. Schematics of the corrector system (nonlinear and skew quadrupoles) around the 6 o'clock IP

from the IR's are in additions to the skew quadrupole families that are used for globally decoupling the machine by minimization of the tune separation at the coupling difference resonance.

4 THE LHC IR CORRECTION SYSTEM

The IR correction system planned for the LHC is based on the same principle of the RHIC IR system.

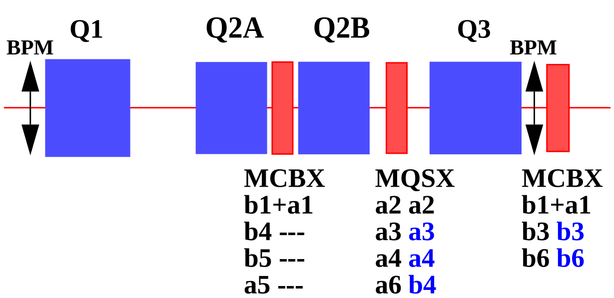

Figure 2. IR Correction system for the LHC.
(European notation for the multipoles)

Figure 2 shows a schematic view of the LHC IR Correction system: 3 corrector packages are placed respectively in the middle of the Q2 cryostat (MCBX-Q2), between Q2 and Q3 (MQSX) and after Q3 (MCBX-Q3). The original IR correction scheme was studied and finalized at the US-LHC BNL Workshop in 1999 [2]. Every MCBX contains a horizontal and vertical dipole corrector, and MQSX a skew quadrupole. The other layers contain high order multipole windings. Recently, a simplified version of the system has been considered, where MCBX-Q2 only retains the 2 dipole correctors, MQSX the skew layers (a2, a3 and a4) and the b4, and MCBX at Q3 contains sextupole and dodecapole windings in addition to the dipole correctors. Overall, the b5, a5, a6 layers were dropped from the original scheme since the corrector strengths required, on tha basis of recent LHC IR magnet measurements, are rather weak.

5 THE MODEL

A complete set of simulation results exists for the *nominal RHIC collision lattice*, (β*=1m at IP6 and IP8, and 10m in all other IP's). The RHIC *off-line model* includes the measured field errors for all relevant magnets in the machine, measured at 5000A (current corresponding to ~100 GeV). The model includes also the *"IR filter"* that calculates the IR correction settings by the "action-kick" minimization procedure, and the *local decoupling algorithm* to set the IR skew quadrupole correctors operationally.

A new modeling effort is necessary to simulate the effect of controlled nonlinearity in the machine (see below) for the *run 2000 lattice* (feb2000a, β*=1m at IP6, β*=8m at IP10 and β*=3m in all other IP's) and possibly field errors measured at 3000 A (current for which we have data closest to 70 GeV).

We also need to bridge the *off-line* to the *online model* by implementing in the latter the capability of reading and writing

SXF files [3].

6 SYSTEM COMMISSIONING

The commissioning of the IR correction system consists of several steps. The prerequisite is to have 1 RHIC Ring (presumably Blue first, then Yellow) *operational* and *stable*. That specifically means: stable circulating beam (lifetime > 1h), orbit corrected in the IR's to <1mm, ΔQ_{min}<0.005, and possibly 1 IP (IP6) squeezed to 1m. Commissioning with β*=3m is possible but all IP's at 3m would contribute equally, a less desirable situation).

6.1 Systems required for IR Correction Commissioning

Other systems, other than the triplet correctors, are necessary for IR Corrections:

Tune Meter. Tune measurements. Possible measurement of tune spread.

Schottky detector. Possible measurement of tune spread.

BPM's (turn-by-turn). FFT analysis (or frequency analysis) of turn-by-turn data to identify spectral lines due to nonlinear fields. For the 2000 run the capability exists of recording 128 turns at every BPM, and ten-thousand's of turns on selected channels.

Orbit Display. Display and correction of orbit. Setting up of IR bumps, off axis in the triplets to measure coupling locally by observing the off plane response and to measure effect of non-linear fields.

DCCT. Measurement of beam lifetime and beam current. Real time (every 10 sec) monitoring and optimization of machine performance.

Ionization Profile Monitor (IPM). Beam profile measurements.

Kickers. To generate oscillations for turn-by-turn BPM acquisition, dynamic aperture measurements, etc. The *tune meter kickers* can be used resonantly. Should that not give a sufficient kick at collision, *injection kickers* can be used for vertical kicking. *Abort kickers* may be used to generate a horizontal kick at collision (in a low intensity machine run, and possibly only with a reduced number of kicker modules active)

AC Dipole. This is the ideal tool to generate a coherent oscillation for IR studies, and will be used for this purpose as soon as on line, likely in the 2001 RHIC run.

6.2 IR Non-linear Correctors

The challenge for the system commissioning is to identify beam observables by which to guide and judge corrector performance. The plan is to test *1 corrector layer (order) at the time* in the following order (american notation for multipoles here):

normal octupole (b3)
normal dodecapole (b5)
normal sextupole(b2)
normal decapole (b4)
skew sextupole(a2)
skew octupole (a3)
skew dodecapole(a5)

Octupole is first because it generates tune spread, a good potential observable. Dodecapole follows since it is an allowed harmonic of the triplet quadrupoles, and also produces tune spread. Skew octupole and dodecapole are at the bottom of the list since they are not powered for this run, given their predicted minimal impact on machine performance.

For every correction layer the following should be done:

1. A "Controlled experiment": apply a known corrector strength, measure the effect on the machine (tune spread, lifetime, spectral lines in turn-by-turn data), and compare with model data. Repeat that at positions of large β_x and β_y if we have 2 correctors in the same triplet (b3, b5 layers).
2. Compensate the effect with a nearby corrector (for the b3 and b5 layers) or with correctors across the IP. Verify the effect on the machine.
3. Set the corrector at the value calculated by the "IR filter" to dead-reckon the measured field error.
4. Operational setting of the corrector based on machine observables (tune spread, real time DDCT, spectral lines).
5. Measurement of machine performance (lifetime, dynamic aperture) with and without correction.

6.3 IR Skew Quadrupole Correctors.

During the early phase of the Year 2000 run a clear coupling effect has been observed in the IR's. By kicking the beam with a horizontal dipole corrector just before an IR, the measured vertical difference orbit shows a clear effect due to the horizontal kick. The horizontal response is in very good agreement with the design machine model. Experimental setting of a triplet skew quadrupole cancels the effect of the orbit. Likely causes of IR coupling are a roll in the IR triplets and skew quadrupole errors in the DX and D0 dipoles at low current.

The plan for IR coupling correction include:

1. Setting up the IR skew quadrupole correctors on the basis of difference orbits analysis. Multiple kicks with different phases will be used to confirm the correction.
2. Measure of local coupling via analysis of turn-by-turn BPM data and local correction (local decoupling algorithm) is planned for the machine run in 2001.

7 IR STUDIES

Once the IR correction system is commissioned there are several IR studies that can increase the knowledge and hopefully the performance of the machine, for instance:

1. Measure the effect of going *off-axis* in the triplets. That will allow to study the effect of feed-down as a function of bump amplitude.
2. Parametric dependence on β* *at IP6*. In the 2000 run IP6 is the only IR with beta squeeze capability (not all IR power supplies were delivered on time). In 2001 it will be possible to squeeze IP8 as well.
3. Effect of *crossing angle.* The design crossing angle at RHIC is zero, however it is possible to achieve crossing angles up to a few mrad by trimming the DX and D0 magnets. A tunable crossing angle opens the possibility of studying the interplay of IR field quality and beam-beam effects, which is very impor-

tant for the LHC. That is particularly interesting with a proton beam where beam-beam effects are expected to be more significant.

8 CONCLUSIONS AND PLANS

The main goal of the IR correction system is improvement of RHIC performance. The IR correction system planned for the LHC is very similar to the RHIC system, so both IR Correction commissioning and IR studies at RHIC are of relevance for the LHC, and in particular for the US-LHC Collaboration. This workshop on "Beam experiments for future hadron colliders" was successful in identifying potential collaborators from which we will benefit during the commissioning and study phases. Collaborative studies, if successful, have the potential to lead in the future to more formally organized beam experiments.

9 REFERENCES

[1] J.Wei, *"Error compensation in insertion region magnets"*, Particle Accelerators, 55 439-448(1996).
[2] Proceeding of the "*Workshop on LHC Interaction region correction systems"*, Ed. W.Fischer and J.Wei, BNL-52575 and LHC Project Note 199.(1999)
[3] H. Grote, J. Holt, N. Malitsky, F. Pilat, R. Talman, C.G. Trahern, *"SXF (Standard eXchange Format): definition, syntax, examples"*, RHIC/AP/155, August 1998.